Original Article

Load-Deflection Characteristics of Superelastic Nickel-Titanium Wires

Theodosia N. Bartzela[a]; Christiane Senn[b]; Andrea Wichelhaus[c]

ABSTRACT

Objective: To determine the mechanical properties of commercially available thermodynamic wires and to classify these wires mathematically into different groups.

Materials and Methods: The samples examined were 48 nickel-titanium (NiTi) alloy orthodontic wires commercially available from five manufacturers. These samples included 0.016-inch, 0.016- × 0.022-inch, 0.017- × 0.025-inch, and 0.018- × 0.025-inch wires. The superelastic properties of the NiTi wires were evaluated by conducting the three-point bending test under uniform testing conditions. The group classification was made under mathematically restricted parameters, and the final classification was according to their clinical plateau length.

Results: The orthodontic wires tested are classified as follows: (1) true superelastic wires, which presented a clinical plateau length of ≥0.5 mm; (2) borderline superelastic with a clinical plateau length of <0.5 mm and >0.05 mm; and (3) nonsuperelastic, with a clinical plateau length of ≤0.05 mm. The results showed that the range of products displays big variations in quantitative and qualitative behavior. A fraction of the tested wires showed weak superelasticity, and others showed no superelasticity. Some of the products showed permanent deformation after the three-point bending test.

Conclusion: A significant fraction of the tested wires showed no or only weak superelasticity. The practitioner should be informed for the load-deflection characteristics of the NiTi orthodontic wires to choose the proper products for the given treatment needs.

KEY WORDS: NiTi wires; Superelastic materials; Superelasticity

INTRODUCTION

Nickel-titanium (NiTi) alloys have been widely used in orthodontics because of their favorable mechanical properties, a remarkable feature of which is their superelasticity.[1,2] NiTi archwires can easily be transformed between an austenite and a martensite phase either by temperature changes or by stress application. The transition between the two phases is termed *martensitic transformation*, and it is responsible for the memory effect. This transformation is the result of changes in the crystal lattice of the material.[3,4] Superelasticity is the transformation from austenitic to martensitic that occurs by stress application within a temperature range and is manifested by a flat or nearly flat plateau in a force-deflection curve.[5]

Shape-memory property is the plastic deformation of NiTi wires from the martensite phase to an austenite crystal structure. The shape-memory properties of archwires can be modified by adding a third element to the NiTi alloy, for example, copper. The copper in the NiTi alloys increases the corrosive resistance and controls the hysteresis width.[6]

The NiTi alloys exert nearly the same amount of force independent of the activation of the wire, thus providing a low magnitude and constant duration of force. Studies have shown, however, that the commercially available NiTi alloys behave in a variable manner, which often deviates from superelasicity.[7] The differences lay in the shape of the force-displacement curve and the position of the superelastic plateau (Figure 1).

To objectively compare different curves, certain parameters have been developed. The superelastic pla-

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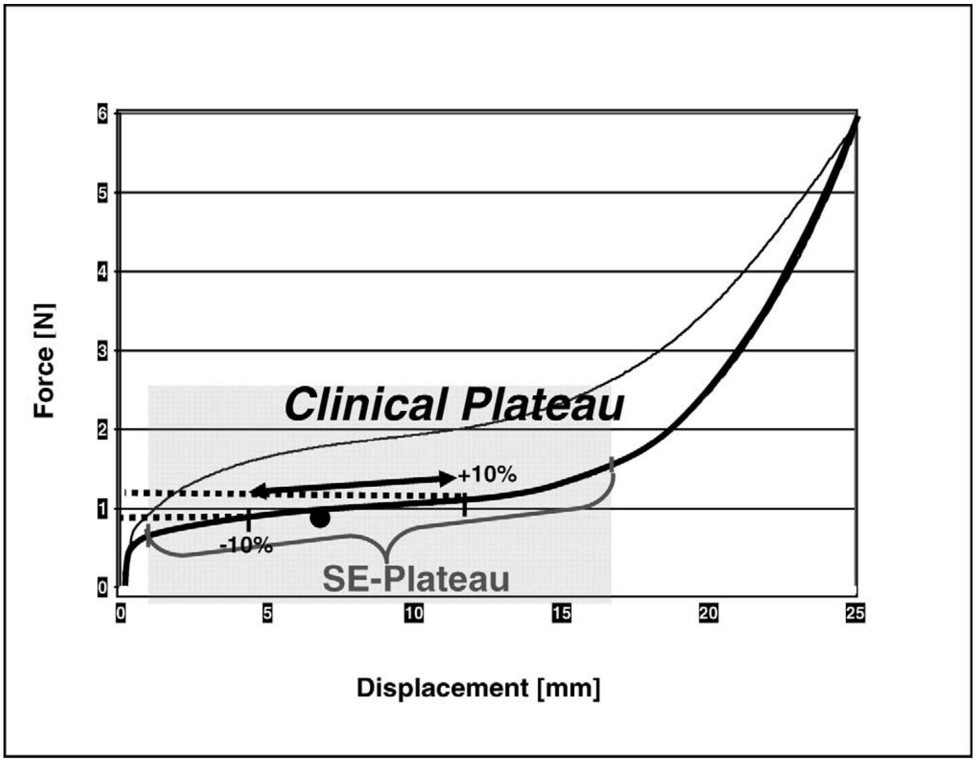

Figure 1. Force-displacement curve. SE-plateau (SEP) indicates superelastic plateau. The clinical plateau is ±10% of the center force of the SEP. ● indicates the center of the SE-plateau; ↔ clinical, plateau length.

teau has been described by the superelastic ratio in a quantitative way (Figure 1).[7] The superelastic properties of the wires depend mainly on the force level of the plateau and to lesser extent on the degree of deflection.[7]

It has been demonstrated that low, continuous forces allow rapid orthodontic tooth movement.[8] This study has been focused more on a clinical concept. The clinical plateau of the unloading curve has been introduced, because in orthodontics, the deactivation curve is the main one of interest in relation to moving teeth (Figure 1).[7] The superelastic properties of the different NiTi alloys have been compared.

The wires have been classified into four different groups according to the force-deflection properties demonstrated in the three-point bending test (Figure 2). It is the aim of the present study to determine the mechanical properties of commercially available thermodynamic wires and to classify these wires mathematically into different groups.

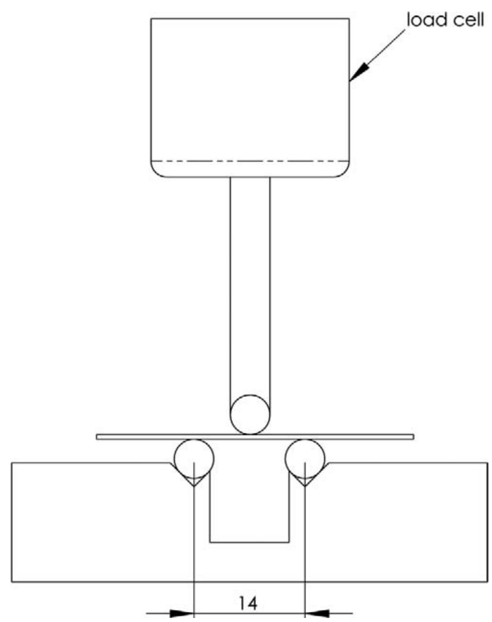

Figure 2. Three-point bending model.

MATERIALS AND METHODS

Materials

The samples examined were 48 NiTi alloy orthodontic wires commercially available from five manufacturers. These samples included 0.016-inch, 0.016- × 0.022-inch, 0.017- × 0.025-inch, and 0.018- × 0.025-inch wires, commonly used for the 0.022 edgewise technique. The wires tested are mainly available as preformed arches. The following wires were evaluated: 15 round wires (0.016 inch) and 33 rectangular cross sections (19 of 0.016- × 0.022-inch, 1 of 0.017-

Table 1. List of Different Wire Types Tested

Product	Wire Size, Inches	Manufacturer
Biostarter	Max 0.016	Forestadent
Cooper NiTi Superelastic at 27°C	Max 0.016; max 0.016 × 0.022	Ormco
Cooper NiTi Thremo Active 35°C	Max 0.016; max 0.016 × 0.022	Ormco
Cooper NiTi Thremo Active 40°C	Max 0.016 × 0.022	Ormco
Dimple Pro Form Nitanium	Max 0.016; max 0.016 × 0.022; max 0.018 × 0.025	Ortho Organizers
Kinetix Thermal Nitanium	Max 0.016; max 0.016 × 0.022; max 0.018 × 0.025	Ortho Organizers
Multi Force	Max 0.016 × 0.022; max 0.018 × 0.025	Ortho Organizers
Nitanium	Max 0.016; max 0.016 × 0.022; max 0.018 × 0.025	Ortho Organizers
Nitanium Total Control	Max 0.016 × 0.022; max 0.018 × 0.025	Ortho Organizers
NiTi	Max 0.016 × 0.022; max 0.018 × 0.025	Ormco
Nitinol Classic	Max 0.016; max 0.016 × 0.022; max 0.018 × 0.025	3M
Nitinol Heat Activated	Max 0.016; max 0.016 × 0.022	3M
Nitinol Super Elastic	Max 0.016; max 0.016 × 0.022; max 0.018 × 0.025	3M
Rematitan Superelastic	Max 0.016; max 0.016 × 0.022; max 0.017 × 0.025	Dentaurum
Thermal Heat Activated	Max 0.016; max 0.016 × 0.022; max 0.018 × 0.025	Dentaurum
Titanol Low Force	Max 0.016; max 0.016 × 0.022; max 0.018 × 0.025	Forestadent
Titanol Martensitic	Max 0.016; max 0.016 × 0.022; max 0.018 × 0.025	Forestadent
Titanol Straight Sections	Max 0.016; max 0.016 × 0.022	Forestadent
Titanol Superelastic S	Max 0.016; max 0.016 × 0.022; max 0.018 × 0.025	Forestadent
Titanol Triple Force	Max 0.016 × 0.022; max 0.018 × 0.025	Forestadent

× 0.025-inch, and 13 of 0.018- × 0.025-inch wires). The wires tested are listed in Table 1.

From each archwire, the two posterior sections were cut and tested. The two posterior sections of three archwires of the same batch were tested. All measurements were conducted under identical testing conditions. The NiTi wires were divided into groups according to the degree of superelastic properties demonstrated in the three-point bending test.

Methods

A three-point bending test was conducted using the universal testing machine (Instron 4444; Instron, Canton, Mass). The load frame was equipped with Instron's ±100 N static cell (Instron 480). The rectangular wires were measured under vertical loads applied on their flat, wide sides. All measurements were taken in a constant temperature chamber of 37.0°C. The temperature was controlled to (±0.5°C) by an external PT100 precise temperature sensor and was maintained stable by a Julabo FS 18 HP thermostat (Julabo, Seelbach, Germany). The suction and compression pumps were connected to the closed air system in an open hydraulic circuit.

The mechanical properties were investigated in three-point bending tests using a beam length of 14 mm (Figure 2).[1,9] Six measurements were recorded for each specimen. The mid portion of the wire segment was deflected at the speed of 0.1 mm/min under the pressure from a metal pole of 5 mm in diameter. Each sample was loaded until a deflection of 3 mm was produced.[9]

The samples were unloaded at the same crosshead speed until the force became zero. The bending tests showed pronounced loading and unloading plateaus. The force-deflection diagrams were drawn from the available data. The unloading curve is the curve of interest for orthodontic tooth movement.[7]

The region of the superelastic plateau was estimated by algorithmetric calculation. The superelastic ratio (SER) was calculated by dividing the slope dF_1/dD_1 (start of unloading curve) and the slope dF_2/dD_2 of the respective data point. The definition of SER was given by Segner and Ibe[7] and modified by Meling and Odegaard.[10]

The superelastic plateau was defined by fulfilling the following condition:

$$SER = >8\frac{dF_1/dD_1}{dF_2/dD_2}$$

After the calculation of the superelastic plateau, the center of the superelastic plateau was defined dividing the superelastic plateau into two equal sections. In this study, the above formula was extended, introducing the clinical plateau. The clinical relevant loading level and the position of the unloading curve were estimated for all the wires examined in the study (Table 1). The estimation of the clinical plateau was ±10% of the center point of the superelastic plateau, scanned on the force-indication axis (Figure 1). Statistically significant differences ($P < .05$) were evaluated for all measurements.

Error of the Method

Six measurements of each wire size have been evaluated to verify the reproducibility of the measure-

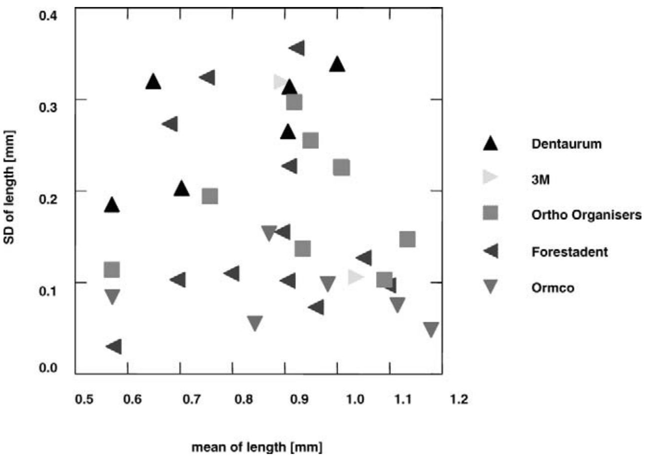

Figure 3. A scatterplot of mean lengths of clinical plateaus (mm) versus standard deviation. Only true superelastic wires are included.

ments. The variability in the repeated measurements of the same type of wire reflects both the variability between individual wires and the measurement error. These two sources of variability cannot be disentangled because the same wire cannot be measured more than once since the test would influence the mechanical properties of the wires. The relation between the standard deviation and the mean value of the clinical plateau length was evaluated (Figure 3). Variability of the superelastic properties between wires of the same batch was observed. Minimal production process changes contribute to the behavior variability of these wires and not the error of the measurements.

RESULTS

Of the 48 NiTi alloy orthodontic wires examined (Table 1), 29 showed true superelastic properties, 9 had no superelastic properties, 7 were borderline superelastic wires, and 3 were classified as borderline nonsuperelastic. Four of the different wire types showed permanent deformation after the three-point bending test.

The results following mathematical analysis showed the difference in the level and length of the plateau for the three different groups of orthodontic wires (Tables 2–5). The qualitative stress-strain behavior was evaluated, and the final classification was according to their clinical plateau length.

According to Segner and Ibe,[7] a plateau value of 0.5 mm is considered a good value and, with the guide of the clinical plateau measurements made in this study, the wires examined were classified into the following groups:

Table 2. True Superelastic NiTi Alloys: Clinical Plateau Length and Mean Forces in the Middle of the Clinical Plateaus

Product	Wire Size, Inches	Mean Clinical Plateau Length, mm	Mean Force in the Middle of the Clinical Plateau, N/mm
Biostarter	Max 0.016	0.82 ± 0.13	0.67 ± 0.11
Cooper NiTi Superelastic at 27°C	Max 0.016	1.11 ± 0.07	0.75 ± 0.04
Cooper NiTi Superelastic at 27°C	Max 0.016 × 0.022	0.98 ± 0.10	1.21 ± 0.08
Cooper NiTi Thremo Active 35°C	Max 0.016	0.84 ± 0.06	0.56 ± 0.05
Dimple ProForm Nitanium	Max 0.016	0.92 ± 0.30	1.26 ± 0.08
Dimple ProForm Nitanium	Max 0.016 × 0.022	1.09 ± 0.10	1.7 ± 0.21
Dimple ProForm Nitanium	Max 0.018 × 0.025	1.01 ± 0.23	2.99 ± 0.52
Kinetix Thermal Nitanium	Max 0.016	0.76 ± 0.19	0.5 ± 0.18
Kinetix Thermal Nitanium	Max 0.016 × 0.022	0.95 ± 0.26	1.0 ± 0.23
Multi Force	Max 0.016 × 0.022	1.13 ± 0.15	1.98 ± 0.08
Multi Force	Max 0.018 × 0.025	1.01 ± 0.22	2.86 ± 0.2
Nitanium	Max 0.016	0.93 ± 0.14	1.12 ± 0.18
NiTi	Max 0.016 × 0.022	1.18 ± 0.05	2.19 ± 0.27
NiTi	Max 0.018 × 0.025	0.87 ± 0.15	2.92 ± 0.39
Nitinol Heat Activated	Max 0.016 × 0.022	1.04 ± 0.11	0.69 ± 0.07
Nitinol Heat Activated	Max 0.016	0.89 ± 0.32	1.32 ± 0.2
Rematitan Superelastic	Max 0.016	1.00 ± 0.34	1.47 ± 0.11
Rematitan Superelastic	Max 0.016 × 0.022	0.91 ± 0.26	2.43 ± 0.33
Thermal Heat Activated	Max 0.016	0.91 ± 0.31	0.64 ± 0.05
Titanol Low Force	Max 0.016	0.91 ± 0.23	0.89 ± 0.14
Titanol Low Force	Max 0.016 × 0.022	0.89 ± 0.16	1.37 ± 0.17
Titanol Martensitic	Max 0.016	0.96 ± 0.07	0.73 ± 0.1
Titanol Martensitic	Max 0.018 × 0.025	0.69 ± 0.10	1.4 ± 0.18
Titanol Straight Sections	Max 0.016	1.10 ± 0.10	1.34 ± 0.04
Titanol Straight Sections	Max 0.016 × 0.022	1.05 ± 0.13	2.58 ± 0.21
Titanol Superelastic S	Max 0.016	0.92 ± 0.36	1.09 ± 0.19
Titanol Superelastic S	Max 0.016 × 0.022	0.80 ± 0.11	1.72 ± 0.46
Titanol Triple Force	Max 0.016 × 0.022	0.90 ± 0.10	1.48 ± 0.16
Titanol Triple Force	Max 0.018 × 0.025	0.57 ± 0.03	1.44 ± 0.14

True superelastic wires, in which the clinical plateau length was ≥0.5 mm

Borderline superelastic or Borderline nonsuperelastic, in which the clinical plateau length was <0.5 mm and >0.05 mm, respectively

Nonsuperelastic, in which the clinical plateau length was ≤0.05 mm

The mean values of clinical plateau length and the standard deviation of these values followed by statistical analysis indicated the group classification according to their mechanical category shown in Tables 2 through 5. In the group classification, if the 95% confidence interval does not include the threshold value of 0.5 mm, then the observed mean is significantly different from this value at a 5% level of confidence.

The results showed that the range of products displays big variations in quantitative and qualitative behavior. A significant fraction of products showed either no or only weak superelasticity. The wires within the same group showed differences in the position and the load level of the clinical plateau.

Ormco and Forestadent showed less variability between the same type of wire products (same batch) in comparison to the other companies (Figure 3).

Mechanical Properties

The true superelastic wires yielded a mean force in the center of the superelastic plateau ranging between 0.56 and 2.99 N (Table 2). The minimum force values were released by the Cooper NiTi Thermoactive 35°C, 0.016-inch wires by Ormco and the maximum value by the Dimple Pro Form Nitanium, 0.018- × 0.025-inch wires by Ortho Organizers (Table 2). The true superelastic 0.016-inch wires demonstrated no significant difference with regard to the plateau length (Table 2).

The only exception was Kinetic Thermal Nitanium produced by Ortho Organizers, which demonstrated the smallest plateau length but also the minimum force released (0.50 N; Table 2). The maximum force among the true superelastic 0.016-inch wires was 1.5 N applied by Rematitan Superelastic supplied by Dentaurum (Table 2).

The qualitative stress-strain behavior was evaluated, and the final classification was according to their clinical plateau length. A selection of the longest plateaus with the true superelastic properties of the 0.0160- × 0.022-inch wires was made. These are the following:

NiTi by Ormco (1.18 mm)
Multi Force by Ortho Organizers (1.13 mm)
Dimple Pro Form Nitanium by Ortho Org (1.09 mm)
Titanol Straight Sections by Forestadent (1.05 mm)
Nitinol Heat Activated by 3M (1.04 mm)

All 0.016- × 0.022-inch wires with true superelastic properties released forces ranging from 0.60 to 2.58 N (Table 2). The minimum values were released by the Cooper NiTi Thermoactive 35°C wire by Ormco and the maximum value by the Nitanium by Ortho Organizers (Table 2). The longest plateaus among the true superelastic wires of 0.017 × 0.025 inches and 0.018 × 0.025 inches were demonstrated from the following products:

Dimple Pro Form Nitanium, Ortho Organizers, 0.018 × 0.025 inches (1.01 mm)

Multi Force, Ortho Organizers, 0.018 × 0.025 inches (1.01 mm)

NiTi, Ormco, 0.018 × 0.025 inches (0.87 mm)

In this study, the 0.017- × 0.025-inch and 0.018- × 0.025-inch wires, with the longest plateaus, have released the greatest forces, in comparison to the smaller dimension true superelastic wires, ranging from 2.86 to 2.99 N (Table 2).

The superelastic properties of some commercially available wires are weak. The Nitinol Superelastic from 3M (claimed by the manufacturer to be superelastic) belongs according to our group classification: the 0.016-inch wire to the nonsuperelastic group, while the two other dimensions (0.016 × 0.022 inches,

Table 3. Nonsuperelastic NiTi Alloys: Clinical Plateau Length and Mean Forces in the Middle of the Clinical Plateaus

Product	Wire Size, Inches	Mean Clinical Plateau Length, mm	Mean Force in the Middle of the Clinical Plateau, N/mm
Cooper NiTi Thremo Active 40°C	Max 0.016 × 0.022	0.12 ± 0.09	0.15 ± 0.03
Kinetix Thermal Nitanium	Max 0.018 × 0.025	0.36 ± 0.10	0.61 ± 0.17
Nitanium	Max 0.018 × 0.025	0.24 ± 0.14	4.2 ± 0.09
Nitanium Total Control	Max 0.016 × 0.022	0.01 ± 0.01	3.93 ± 0.13
Nitanium Total Control	Max 0.018 × 0.025	NA[a]	NA[a]
Nitinol Classic	Max 0.016	0.02 ± 0.02	2.39 ± 0.24
Nitinol Classic	Max 0.016 × 0.022	0.02 ± 0.01	3.75 ± 0.24
Nitinol Classic	Max 0.018 × 0.025	0.02 ± 0.01	5.89 ± 0.88
Nitinol Super Elastic	Max 0.016	0.13 ± 0.09	1.39 ± 0.11

[a] NA indicates not applicable.

Table 4. Borderline Superelastic NiTi Alloys: Clinical Plateau Length and Mean Forces in the Middle of the Clinical Plateaus

Product	Wire Size, Inches	Mean Clinical Plateau Length, mm	Mean Force in the Middle of the Clinical Plateau, N/mm
Cooper NiTi Thremo Active 35°C	Max 0.016 × 0.022	0.57 ± 0.08	0.6 ± 0.09
Nitanium	Max 0.016 × 0.022	0.57 ± 0.11	2.58 ± 0.33
Rematitan Superelastic	Max 0.017 × 0.025	0.65 ± 0.32	2.72 ± 0.33
Thermal Heat Activated	Max 0.016 × 0.022	0.70 ± 0.20	0.77 ± 0.23
Thermal Heat Activated	Max 0.018 × 0.025	0.57 ± 0.19	1.03 ± 0.38
Titanol Martensitic	Max 0.016 × 0.022	0.68 ± 0.27	0.77 ± 0.28
Titanol Superelastic S	Max 0.018 × 0.025	0.75 ± 0.32	2.66 ± 0.63

0.018 × 0.025 inches) to the borderline nonsuperelastic group (Tables 3 and 5).

The wires with nonsuperelastic behavior demonstrated mean forces in the center of superelastic plateau ranging from 0.15 to 5.89 N (Table 2). Some wires showed a permanent deformation after the final activation of 3 mm (Table 6). The Nitanium Total Control 0.018- × 0.025-inch wire and the NiTi 0.018- × 0.025-inch wire showed a permanent deformation in all six samples tested (Table 6). The Cooper NiTi Thermo Active 40°C (0.016 × 0.022 inches) and the Nitanium Total Control (0.016 × 0.022 inches) showed a permanent deformation in one or four of the samples tested, respectively (Table 6).

DISCUSSION

The standard method for evaluating orthodontic wires not containing precious metals is the three-point elastic bending test according to ADA specification no. 32.[11] The results of this method for evaluating the practical value of these wires has been under consideration,[1] and a five-point elastic bending test was proposed, imitating more of the clinical process.[12] Later, Hurst et al[13] designed special grips to hold the wire in place in the Instron machine.

It is not possible to transfer the laboratory results of the above mentioned test or modification of this test to the clinical orthodontic setting. Only patients with extreme irregularities experience deflections greater than 1.0 mm,[7] and in routine orthodontic treatment, the deformation of NiTi wires is not sufficient to take advantage of their superelastic behavior.[2] Also, the force levels applied in vivo may not reach the superelastic plateau, and the force would not be independent of deflection.[2] There are testing methods focusing directly on the orthodontic system or others that are pure evaluation of physical and biomechanical properties of the wires.

The three-point bending method is not directly transferable to the clinical setting and resembles occlusogingival movements.[14] The three-point bending has been employed as a physical property test.[14] It is a method focusing more on the physical and biomechanical properties of the wires, offers reproducibility, and is useful for purely theoretical evaluations. It is a standardized testing method that makes comparison to other studies possible.[15,16]

The laboratory tests are not capable of revealing the major characteristics of the new available wires. Such tests should be a comparison between laboratory findings and findings obtained from clinical trials.[17] Settings were described by Gross[18] and later by Segner and Ibe[7] that resemble the orthodontic clinical situation, the three-bracket bending system. The stiffness values of NiTi wires in 3 mm of deflection in the bracket bending test exceed 7.5 to 40 times the stiffness values of the three-point bending test.[14]

In a clinical setting, it is almost impossible to make assessments on the strain that is exerted on the archwire.[7] Factors such as friction should also be considered. Friction increases the effective force in the activation mode, and it decreases the force in the deactivation mode. In this way, the force deflection curve may be distorted.[7]

The clinical plateau was introduced so that a more clinically relevant measure could be attained that allows a classification of the wires according to their superelastic properties. The new definition was based on the superelastic ratio described by Segner and Ibe[7] and further modified by Meling and Odegaard.[10] These

Table 5. Borderline Nonsuperelastic NiTi Alloys: Clinical Plateau Length and Mean Forces in the Middle of the Clinical Plateaus

Product	Wire Size, Inches	Mean Clinical Plateau Length, mm	Mean Force in the Middle of the Clinical Plateau, N/mm
Nitinol Super Elastic	Max 0.016 × 0.022	0.34 ± 0.22	2.68 ± 0.16
Nitinol Super Elastic	Max 0.018 × 0.025	0.47 ± 0.19	3.12 ± 0.28
Titanol Low Force	Max 0.018 × 0.025	0.40 ± 0.11	0.59 ± 0.19

Table 6. Wires With Permanent Deformation After the Three-Point Bending Test

Product	Wire Size, Inches	Manufacturer
Cooper NiTi Thremo Active 40°C	Max 0.016 × 0.022	Ormco
Nitanium Total Control	Max 0.016 × 0.022; max 0.018 × 0.025	Ortho Organizers
NiTi	Max 0.018 × 0.025	Ormco

parameters were developed so that more objective criteria could be established for the evaluation of the different products.

The group classification was made under mathematically restricted parameters. The clinical plateau showed a big variety in length and load level within the groups (Tables 2–5). The wires with longer clinical plateaus are classified as true superelastic and provide relatively stable forces, indicating the best clinical performance. The clinical advantage of using these types of wires is the ability to apply relatively low and stable force levels for the first phase of treatment with fixed appliances.

The measurements of this study are not in agreement with the results of Segner and Ibe[7] in that wires with larger dimensions indicated the best superelastic properties.

According to Garrec et al,[19] the minimal application forces in the three-point bending test were demonstrated by the bigger size of rectangular wires. In this study, only the following 0.018- × 0.022-inch wires displayed lower forces than the smaller dimension rectangular wires tested from the same manufacturer:

Titanol low force by Dentaurum
Kinetix Thermal Nitanium by Ortho Organizers

The true superelastic wires are applicable where large deflections are required and relatively constant force during major stages of tooth movements is needed. In the clinical application, the unloading forces are of main importance. The smaller plateau slope in the unloading phase is an indication for lower as well as constant forces on the clinical application.[7]

The wires with a longer clinical plateau in combination with greater application forces are indicated for derotational procedures. In agreement with the above findings are the results of Andreasen and Morrow,[20] in which the large Nitinol archwires are appropriate to correct and maintain leveling and rotations without increasing the patient's discomfort.

According to the results of this study, the true superelastic wires are indicated for the leveling and the borderline superelastic wires with long plateau length for derotational procedures. The true superelastic wires should be recommended especially for the treatment of adult patients and stark crowding cases. The borderline superelastic archwires are considered suitable for mild to moderate crowding cases.

CONCLUSIONS

The groups of orthodontic wires according to their clinical plateau length can be classified as follows:

- True superelastic wires, which presented with a clinical plateau length of $\geq$0.5 mm
- Borderline superelastic or borderline nonsuperelastic wires with a clinical plateau length $<$0.5 mm and $>$0.05 mm, respectively
- Nonsuperelastic wires, with a clinical plateau length of $\leq$0.05 mm

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